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FILTER DEBRIS ANALYSIS - A CONCRETE APPROACH TO WEAR DIAGNOSIS

by

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ABSTRACT

The diagnostic merits of microscopic inspection and chemical analysis of metallic debris recovered from lubricating oil filters in a variety of oil-wetted machinery are discussed. The filter cleaning method and how it affects the amount of debris recovered is considered. The significance of representative debris levels and some criteria for establishing these levels are discussed. Abnormal debris accumulations and the corresponding mechanical malfunctions are presented to illustrate how filter debris analysis can be used to diagnose increased component wear in a variety of machinery. Merits for application of this technique for the diagnosis of machinery condition are considered. The report concludes that this method of assessing wear is particularly suited for equipment fitted with fine lubricating oil filters and is recommended as a complement to other methods currently used for machinery condition monitoring.

INTRODUCTION

Since the inception of machinery health monitoring, atomic emission[1] and atomic absorption spectrometry[2,3] have been used extensively to obtain information for assessing the mechanical condition of machinery. These techniques have been effective preventative maintenance tools and many mechanical malfunctions have been predicted; however, several failures were not detected because of the limited sensitivity of these techniques to the large wear particles which are produced at failure initiation. There was a requirement, therefore, for methodology which was more sensitive to these large particles.

About fifteen years ago ferrography[4,5,6] was developed to fulfill this requirement. With the advent of ferrography considerable attention was focussed on the size and morphology of wear particles. Thus, a new approach to condition monitoring called wear particle analysis began.

Because wear particle analysis was new, considerable effort was required to establish base line levels for each type of equipment and to determine the significance of the variety of wear particles observed. After extensive experimentation, it was concluded that ferrography was best suited as a complementary technique to the traditional methods[7,8]. Almost coincidental with this conclusion was a trend to the use of fine filters as a means of removing potentially harmful debris from some oil-wetted systems. This prompted the realisation that spectrometric and ferrographic methods are based on the analysis of a lubricant sample for dissolved or particulate contamination, and the use of fine filters would remove virtually all metallic debris of diagnostic significance. Thus, the effectiveness of these methods would be greatly reduced.

As a possible alternative method, Defence Research Establishment Pacific (DREP) investigated the diagnostic potential of

debris entrapped in oil filters from a variety of machinery lubricated with mineral and synthetic lubricants. Objectives of the study were to devise suitable techniques for the efficient removal of debris from different types of filters, to establish representative wear thresholds for each type of machinery and to correlate observations and results with mechanical condition so that filter debris analysis (FDA) could be established as a viable condition monitoring method.

This report describes debris removal procedures for different types of filters, illustrates wear threshold levels for a variety of machinery and cites examples to show how FDA was used for effective diagnosis of equipment mechanical condition.

BASIS FOR FILTER DEBRIS ANALYSIS

Figure 1 shows the debris recovered from the lubricants of three gas turbine engines fitted with 10(a), 25(b) and 47(c) micron oil filters, respectively. As expected, there was a less debris in b than c. Further, the 10 micron filter removed virtually all of the debris from the lubricating system. This debris is shown in Figure 2. While filter efficiency is desirable for removing potentially harmful debris from a system, it follows that the effectiveness of analytical methods such as atomic absorption and/or emission spectrometry and ferrography, which are dependent on oil-borne particulates for diagnostic information, will be greatly reduced. A logical step, therefore, was to investigate the relationship of entrapped debris to mechanical condition.

TYPES OF MACHINERY MONITORED

The relationship of filter debris analysis to mechanical condition was studied for the following types of machinery:

1. gearboxes;

2. gas turbine engines;
3. diesel engines;
4. auxiliary machinery; and
5. turbo-propeller engines.

DEBRIS REMOVAL PROCESSES

Two types of oil filters are fitted in the equipment studied, wafer-type and cartridge-type. For efficient removal of at least 90% of entrapped debris two cleaning procedures are used. With wafer-type filters (Figure 3), which are mechanically held together, the units are disassembled and all components are ultrasonically cleaned in Freon 113 for thirty minutes. With cartridge-type filters (Figure 4) the units are immersed in Freon and ultrasonically cleaned and backflushed with a pulsating current of air for two 15-minute intervals. The apparatus for producing a pulsating current of air is shown in Figure 5. To obtain simultaneous ultrasonic cleaning and backflushing, one end of the filter is plugged and the other end is connected to the pulsed air supply. The filter is then immersed in Freon in a glass jar with a vented lid. The assembly (Figure 6) is placed in an ultrasonic bath. During ultrasonic cleaning, pulsed air at 2 psig is forced through the filter in a direction counter to oil flow. At the end of the first 15-minute period the filter is inverted, the Freon is replenished for evaporation loss and the procedure is repeated for a second 15-minute interval. Following the cleaning procedures the Freon is filtered through a 0.8 μm Millipore membrane and the resulting debris is washed with Freon, dried and weighed.

Debris extracted from oil filters can then be examined with a zoom stereo microscope. The zoom feature of the microscope permits examination of wear particles at continuous magnifications up to 80X. If a more detailed examination of particle morphology is required a compound microscope with magnifications up to 1000X or a Scanning Electron Microscope may be used.

REPRESENTATIVE WEAR

In general, filter debris contains a mixture of both non-metallic and metallic constituents. In many cases the non-metallic portion, which usually has no diagnostic significance, may represent up to 70% of the total debris weight. The remaining portion consists of metal and metallic oxides. Thus, the total debris weight is not necessarily indicative of mechanical condition and should not be used indiscriminately for condition diagnosis. It is necessary to establish representative or normal wear particle levels as a basis for distinguishing between debris produced by normal operational conditions and abnormal or pre-failure conditions.

Representative levels of debris varied among the machinery studied. These differences are sufficient to warrant establishing separate metallic background levels for each type of equipment, or even each individual piece of machinery. Representative wear debris levels for four different types of machinery are shown in Figure 7. The major metallic constituents are dependent on the material compositions of the components. For the machinery studied to date, metallic constituents included ferrous, aluminum-, copper-, magnesium- and nickel-base wear particles. Silver-plated brass or silver-plated bronze particles are occasionally observed in debris from gas turbine engines.

Metallic particles produced during normal wear can vary in size and shape and represent several individual wear modes. Since FDA is a subjective approach to wear assessment, it is important that the relationship between particle amount, size and morphology be established for normal conditions of operation because the sudden change of this relationship signals the onset of failure. It follows, therefore, that representative wear cannot be established for a machine until the amount and variety of particles which are produced during wear-in have been removed by oil and filter changes, and the unit has settled into a normal

wear pattern as judged by data from repeated filter debris analyses. For example, a large amount of thin, flat ferrous platelets with regular peripheries are usually produced during equipment wear-in. After wear-in production of these particles is reduced substantially. A sudden increase may be an early indication of an impending anomaly. Occasionally, small cutting wear particles or particles with burnished and/or striated surfaces are noted. These particles are typical of advanced wear. While it is not unusual to observe several of these particles during wear-in and occasionally during normal wear, they do not represent the major metallic portion of normal wear accumulations. Thus, an appreciable increase in size and amount of these particles relative to other debris constituents should be verified. It must be emphasised, however, that a sudden single deviation from a representative wear pattern should not be construed as an indication of impending malfunction. In all suspect cases verification of the wear condition by repeated filter debris analyses and wear particle identification by an appropriate method such as Scanning Electron Microscope/Energy Dispersive Spectrometry (SEMEDS) is advised.

ABNORMAL DEBRIS ACCUMULATIONS AND CORRESPONDING MALFUNCTIONS

The sensitivity of filter debris analysis to incipient failure in oil-wetted machinery is illustrated by the following examples.

1. Increased Wear of Copper-base Components in a Marine Diesel Engine

Figure 8 shows a section of an oil filter disc from a marine diesel engine. The unit was in operation for 1000 hours. Usually these discs are virtually free of wear debris. In this case, however, visual inspection of the oil filter provided strong evidence of increased wear of a copper-base component. Supportive evidence of impending failure was provided by SEMEDS which indicated that the wear particle composition approximated ASTM alloy B143 (tin bronze). Reference to the schematic drawing for the engine showed that the piston pin bushings were manufactured from a bronze of this type. Tear-down inspection of the

engine revealed excessive wear of two bushings. The worn condition of these bushings is shown in Figure 9.

2. The Detection of Non-mechanical Contamination in a Turbo-Alternator Oil Filter

Condition monitoring is usually conducted to detect incipient mechanical failure in equipment. One of the advantages of FDA is the capability to provide information on other types of abnormal operational conditions, for example rust build-up in machinery. In this example FDA was used to detect non-mechanical deterioration in a turbo-alternator. The differential pressure in this turbo-alternator increased above an acceptable limit. Examination of the oil filter revealed a very heavy accumulation of rust (Figure 10). This suggested that moisture entered the system and caused severe rusting of components. Several oil and filter changes were required to clean the system.

3. Helicopter Gearbox Washer Support and Bearing Failure

Figure 11 shovs debris recovered from two oil filters in a helicopter gearbox. With these gearboxes copper-base particles are seldom observed during normal operation. Thus, the sudden appearance of the amount shown in Figure 11 strongly suggested imminent component malfunction. Microscopic inspection of the debris revealed that a minor amount of ferrous wear particles was also present. SEMEDS analysis of selected copper-base particles indicated a composition which conformed to the specification for a 90-10 tin bronze. Tear-down inspection showed that the copper-base washer support had deteriorated and that excessive circumferential scoring of the input cone bearing had occurred. Secondary damage to other components had also taken place.

4. Extraction Pump Bearing Failure

The differential pressure in an extraction pump increased very

rapidly over a short period of operation. FDA revealed the presence of an unusual amount of ferrous and tin-base wear particles (Figure 12, A). Debris (Figure 12, B and C) from two successive filters confirmed the wear condition. Tear-down inspection showed that advanced wear (Figure 13) of babbitted thrust bearings had occurred.

5. Helicopter Gearbox Bearing Failure

Debris (Figure 14) recovered from the oil filters in a helicopter gearbox after 300 hours of operation contained many ferrous particles up to 2 mm long. Relative to representative wear the metallic portion was considered excessive. In addition, several of the particles displayed characteristics suggesting increased component wear, for example indented peripheries and striated surfaces. SEMEDS analysis of several particles indicated a composition which conformed to the material specification for AISI E52100 bearing steel (Figure 15). Remedial action consisted of an oil change and FDA of a second set of filters after a short period of operation. The wear condition was confirmed. Tear-down inspection showed that several ferrous components had worn excessively, and that advanced fatigue flaking of the input cover bearing had occurred.

6. Increased Wear of Speed Decreaser Gearbox Planet Gear Bearing Cage

Figure 16(a) shows debris recovered from a speed decreaser gearbox oil filter after 337 hours of operation. Debris recovered from the same gearbox after an additional operational period of only 37 hours is shown in Figure 16(b). Visual examination of the debris revealed that a substantial increase in copper-base and ferrous wear particle content occurred during the latter period. Microscopic inspection of the debris showed that wear particle size ranged up to 3 mm and 2 mm for copper-base and ferrous particles, respectively. In addition, an unusual amount of heat-discoloured ferrous particles was observed. SEMEDS analysis of representative particles indicated that the copper-base material (Figure 17) conformed to UNS Specification C87200 for silicon bronze and the

ferrous material to AISI E52100 for bearing steel. Tear-down inspection of the gearbox revealed that the planet gear bearing cage was rubbing against the outer race of the bearing.

7. Gas Turbine Engine Bearing Failure

Debris recovered from an oil filter in a gas turbine engine contained a few particles of AISI E52100 bearing and E9300 series low alloy steels. Particle size ranged up to 3 mm. These particles were not present in a sufficiently large quantity to cause immediate concern. Debris (Figure 18) from a second filter which was removed after an additional 80 hours of operation showed a substantial increase in copper-base wear particles. Microscopic inspection revealed the presence of cutting wear particles and particles with striated surfaces. Particle size ranged up to 2 mm. SEMEDS analysis of selected particles indicated that they were brass (70/30 Cu/Zn). Several of these particles displayed silver-plated surfaces (Figure 19), which suggested extensive wear of bearing cages. Tear-down inspection of the unit revealed that disintegration of a bearing was imminent.

MERITS OF FILTER DEBRIS ANALYSIS FOR MACHINERY CONDITION MONITORING

In assessing the merits of FDA for the routine condition monitoring of oil-wetted machinery, consideration should be given to the following:

1. the oil filter pore size;
2. the representativeness of the sample;
3. an appropriate sampling interval to apply FDA; and
4. the benefits to be derived from an FDA program.

Oil filters with pore sizes of 25 μm or smaller remove virtually all contamination of diagnostic significance. Thus, for machinery fitted with these fine filters FDA is appropriate.

After proper lubricant circulation is established in a machine, debris entrapped in the oil filter is always representative of the wear processes which are occurring inside that machine. Examination of this debris enables identification of these processes and subsequent diagnosis of the mechanical condition of the equipment.

With respect to an appropriate sampling interval, FDA may require in-shop removal of a filter. During this investigation the majority of filters were removed from machinery during normal periodic inspections. On other occasions filters were removed when spectrometric oil analysis, vibration analysis or an abnormal differential pressure suggested a possible wear anomaly. In practice, monitoring frequency should be established so that maximum benefits, including cost-effectiveness, are derived.

In considering the merits of the FDA technique further, it must be remembered that no single monitoring technique is truly free of shortcomings. Also, no method appears to give the definite "go-no-go" answer which an analyst often seeks when a decision has to be made on a course of action. However, FDA provides a concrete approach to the evaluation of machinery wear and, as illustrated by the examples, is particularly suited for machinery fitted with fine lubricating oil filters.

SUMMARY

An investigation to determine the potential of filter debris analysis (FDA) for wear assessment and early failure diagnosis in oil-wetted machinery has revealed that:

1. the major constituent in filters was of non-metallic origin. The minor constituent was primarily a mixture of metal particles originating from machinery components;

2. the weight of debris recovered from a filter or the extent of contamination was not necessarily indicative of the mechanical condition of the machinery. For effective diagnosis, representative levels of debris must be established for all machinery;

3. the single recovery of an amount of metallic debris which is greater than representative wear should not be construed as conclusive evidence of an impending malfunction. For effective diagnosis, suspected anomalies should be verified;

4. distinct differences in wear particle amount, size and morphology constitute the principal distinguishing features between representative wear and abnormal wear; and

5. confirmation of suspected anomalies is enhanced by wear particle analysis which enables identification of material specification and thus, the component source of the wear particles.

CONCLUSION

The examples described in this report demonstrated that the examination and chemical analysis of metallic debris in oil filters provided advance warning of increased wear in a variety of oil-wetted machinery. The technique is particularly suited for equipment fitted with fine lubricating oil filters and is recommended as an invaluable addition to other methods in current use for machinery condition monitoring.

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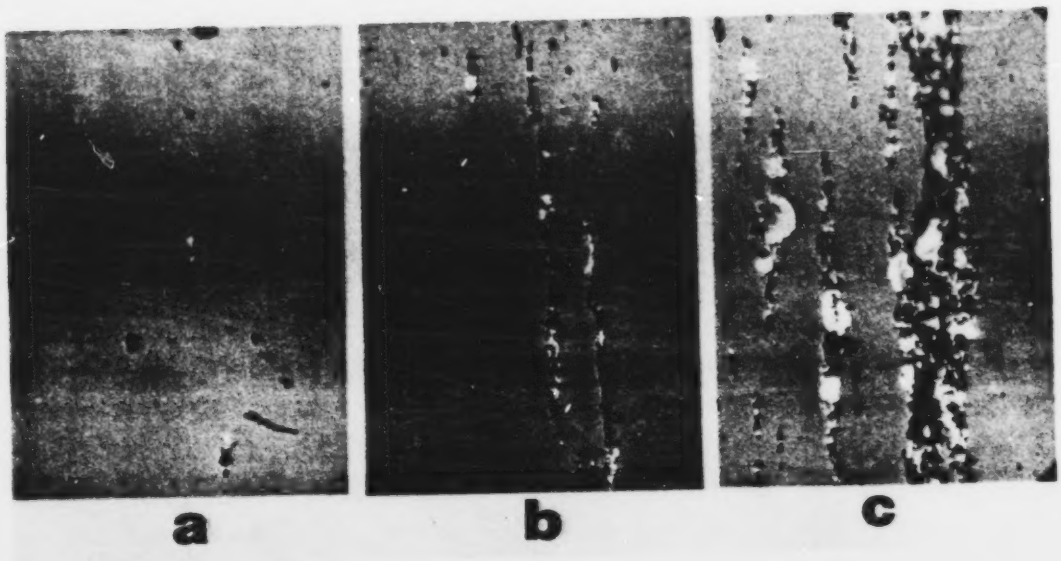


Figure 1. Debris in Engine Oil System After Filtration by 10(a), 25(b) and 47(c) Micron Oil Filter. X 200

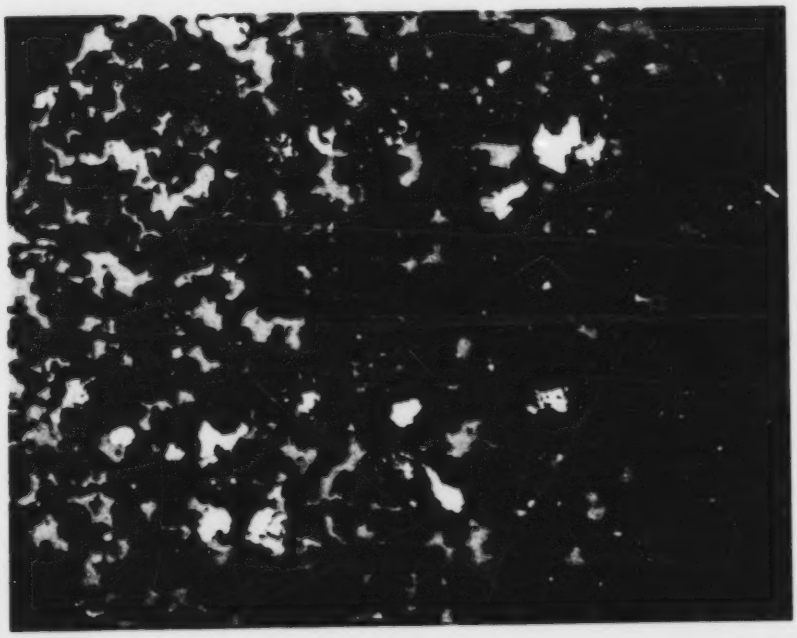


Figure 2. Debris Recovered from a 10 micron Oil Filter. X 200

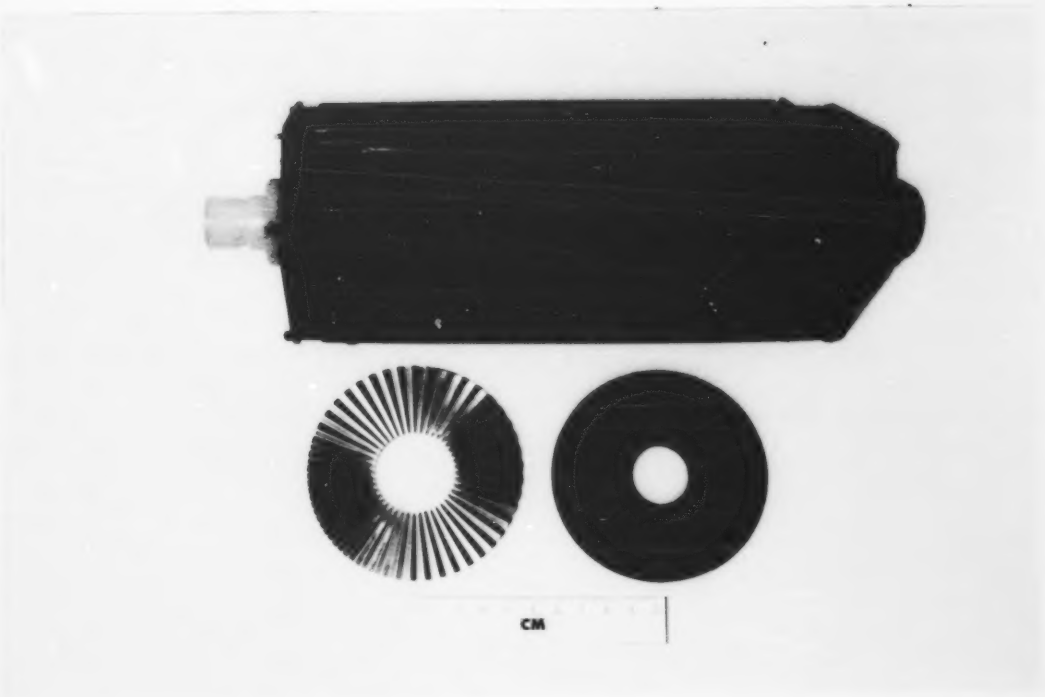


Figure 3. Wafer-type Oil Filter.

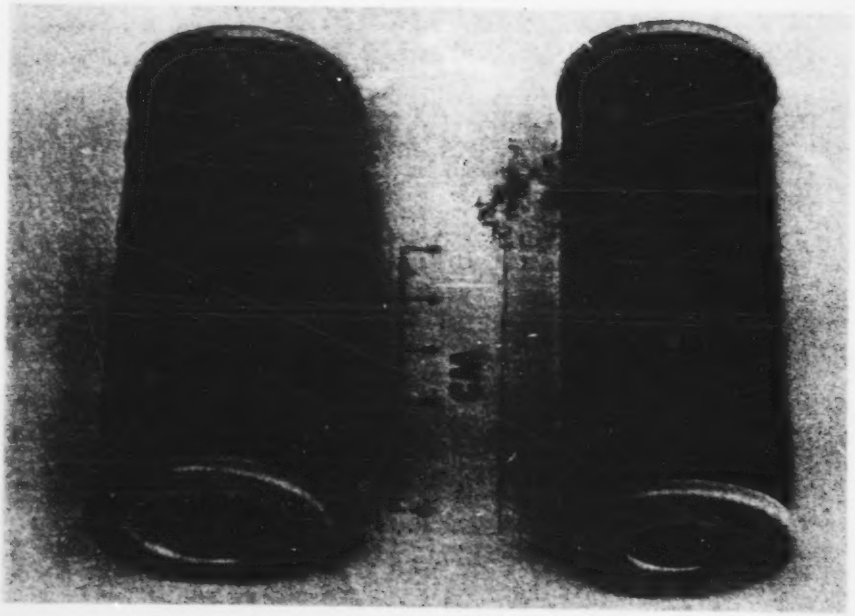


Figure 4. Cartridge-type Oil Filters.

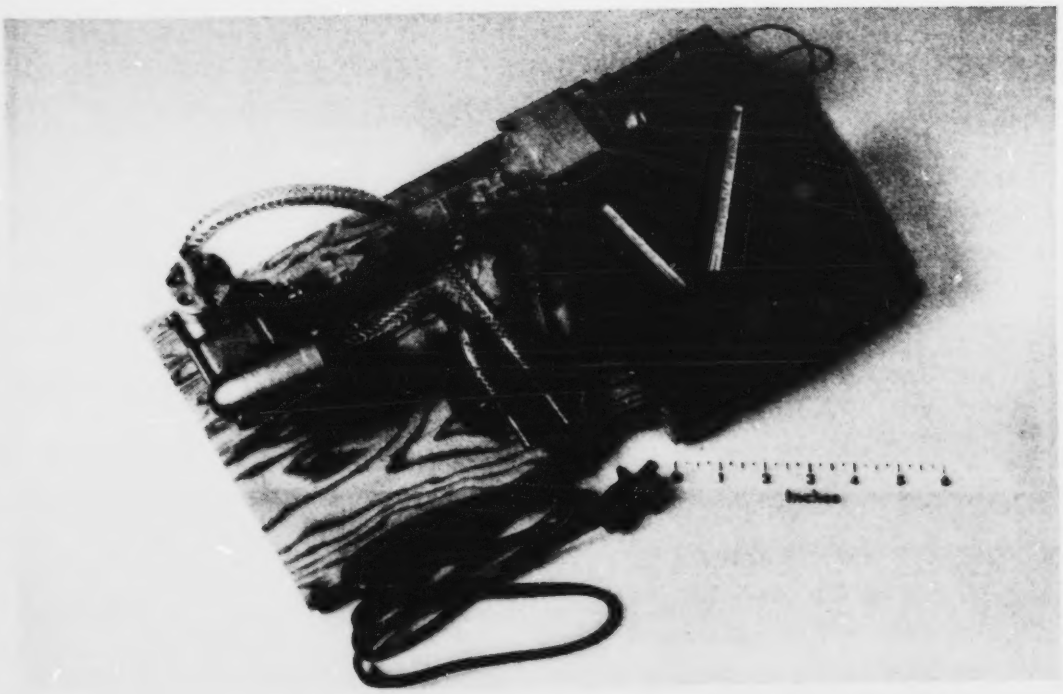


Figure 5. Apparatus for Producing a Pulsating Current of Air.

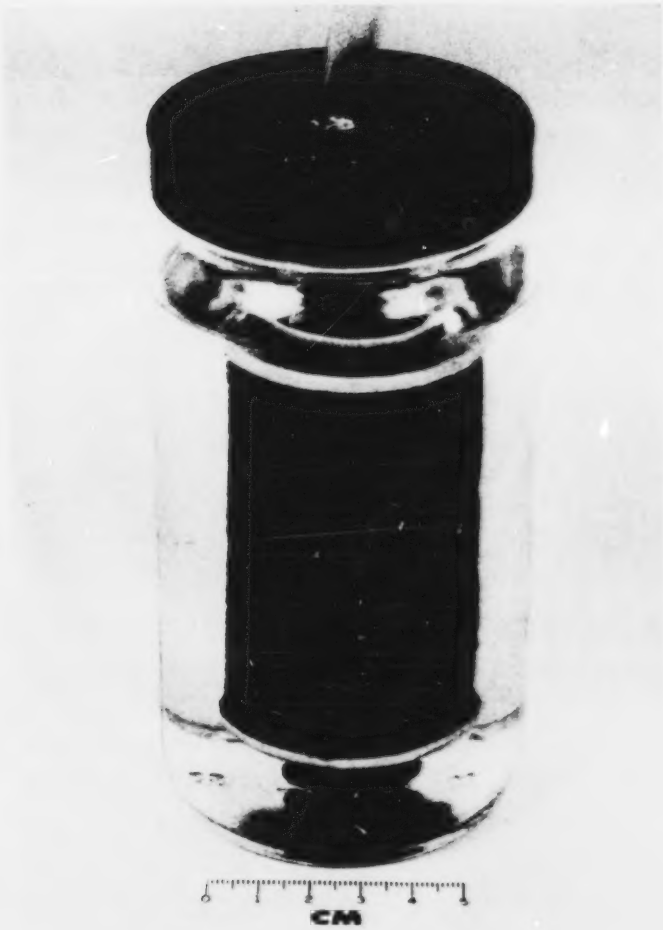


Figure 6. Plugged Cartridge-type Filter Immersed in Freon in Preparation for Ultrasonic Cleaning and Backflushing.

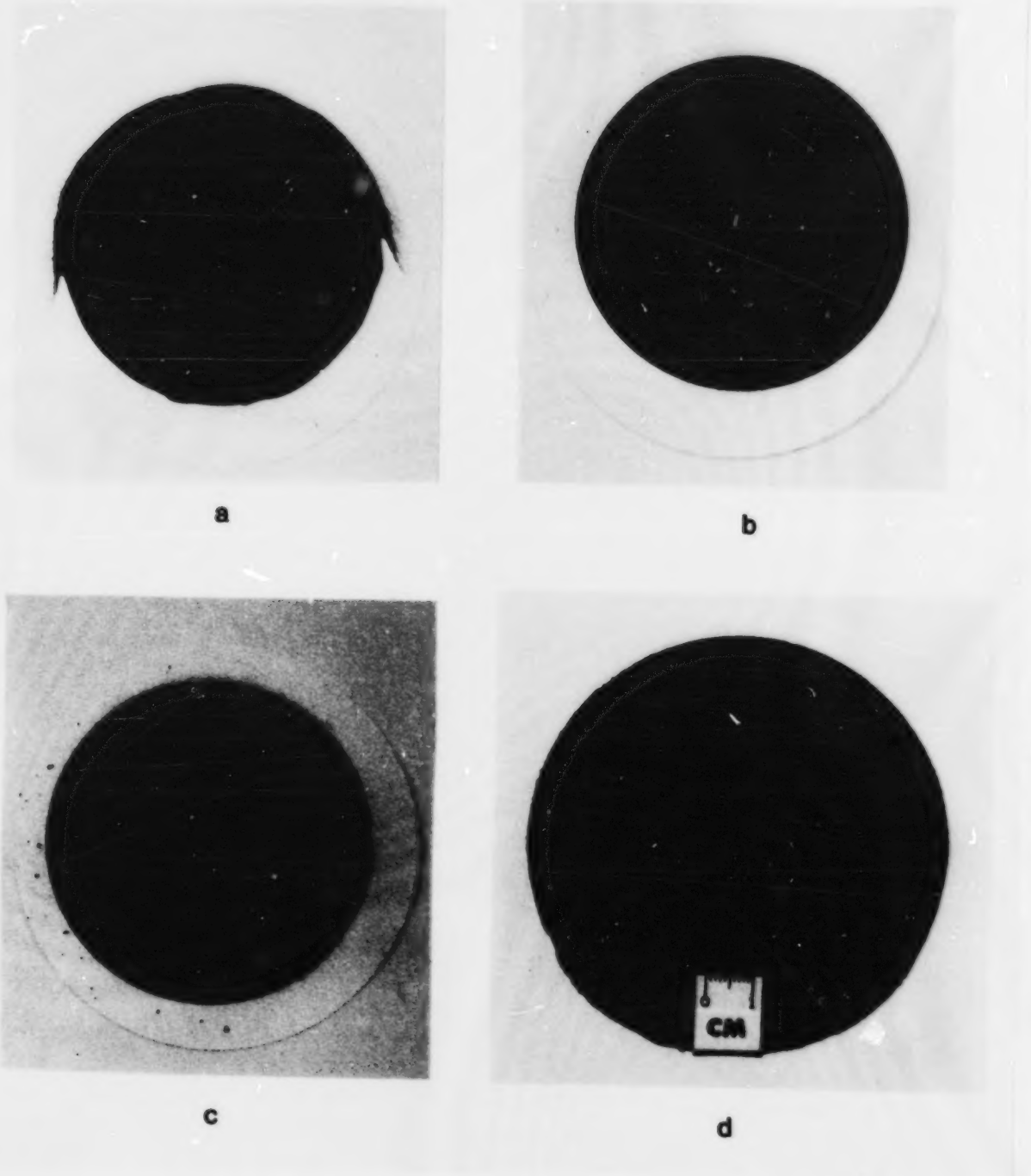


Figure 7. Representative Wear Debris for (a) Gas Turbine Engine b) Turbo-propellor Engine (c) Gearbox (d) Auxiliary Machinery. X 1.5 (a,b, c).

Figure 8. Section of Diesel Engine Oil Filter Showing Accumulation of Copper-base Wear Particles.

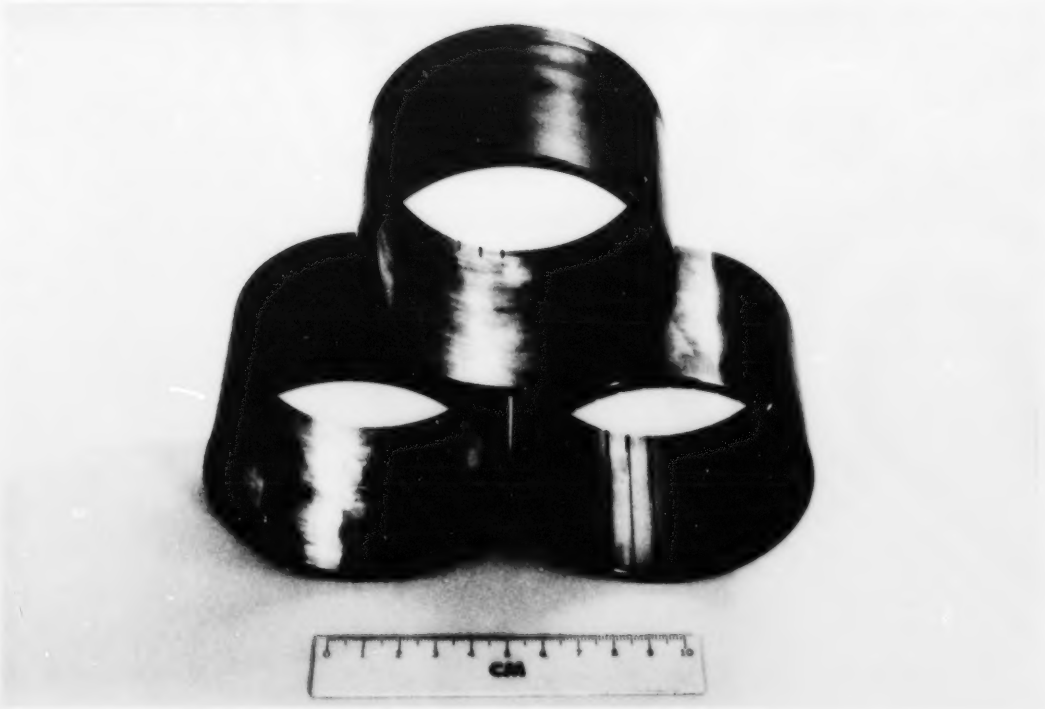


Figure 9. Photograph Showing Comparison Between Worn Piston Pin Bushings and New Bushing (lower right). Note: Disappearance of Oil Grooves and Appearance of Ridges on the Outer Surfaces of Worn Bushings.

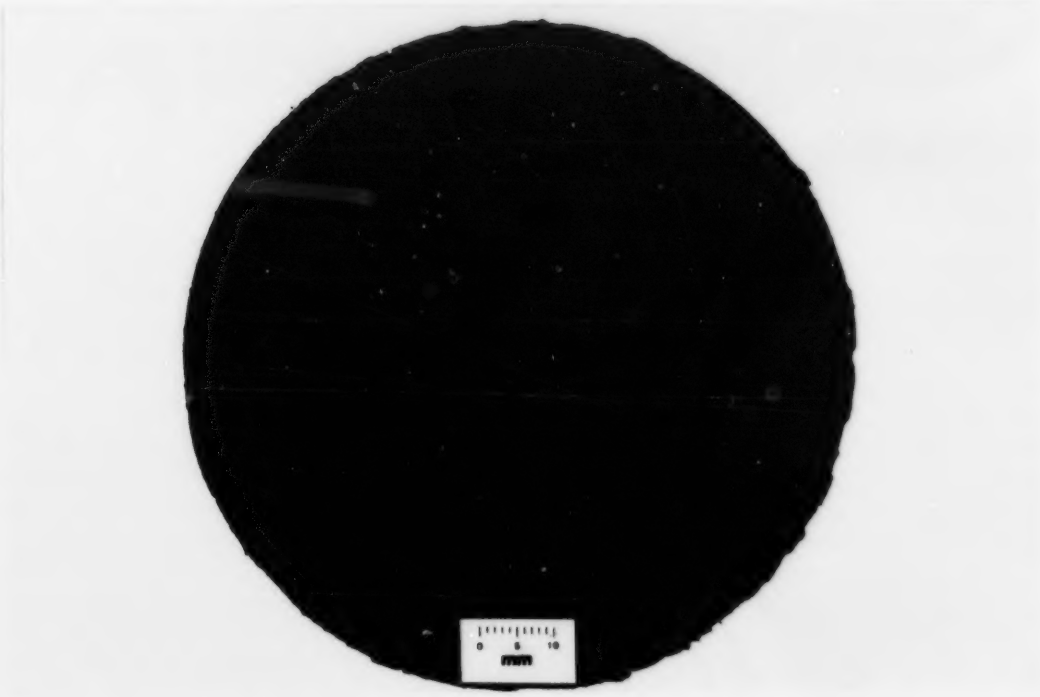


Figure 10. Heavy Rust Accumulation in Oil Filter from a Turbo-Alternator.

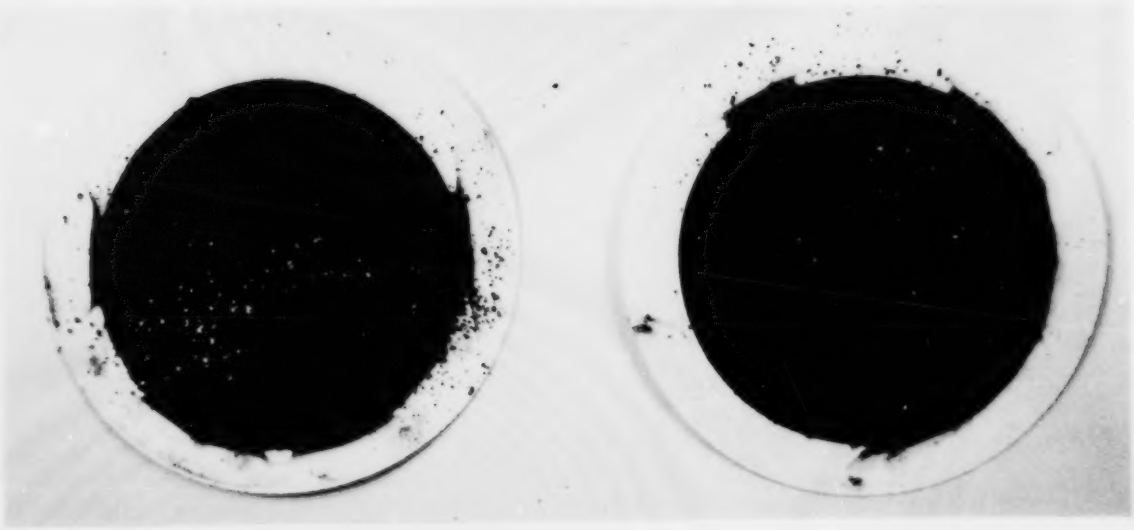
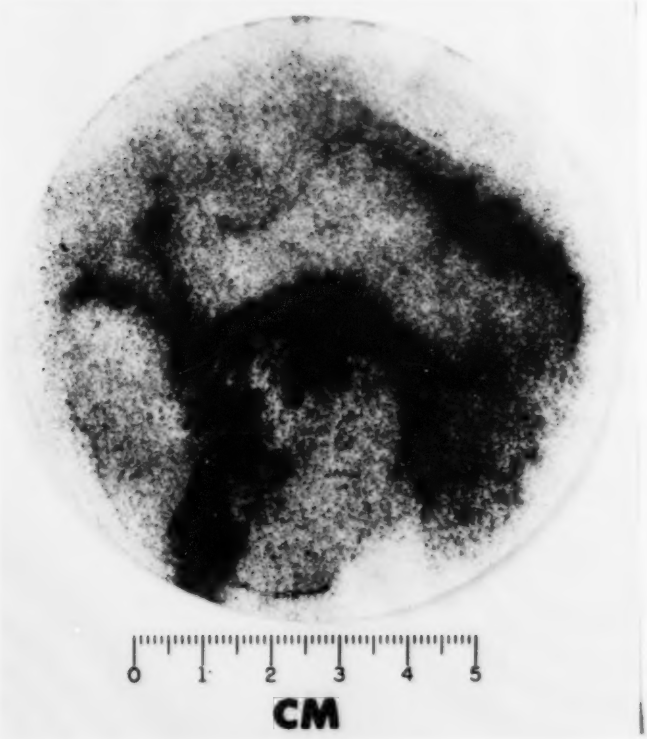


Figure 11. Excessive Amount of Copper-base Debris in a Helicopter Gearbox Oil Filter. X 1.5



A (left) - Debris in filter after 48 hours of operation.

B (below) - Debris in second filter after 8-hour basin trial.

C (left) - Debris in a third filter after approximately 130 hours of operation.

Figure 12. Increasing Amount of Debris in Oil Filters from an Extraction Pump.

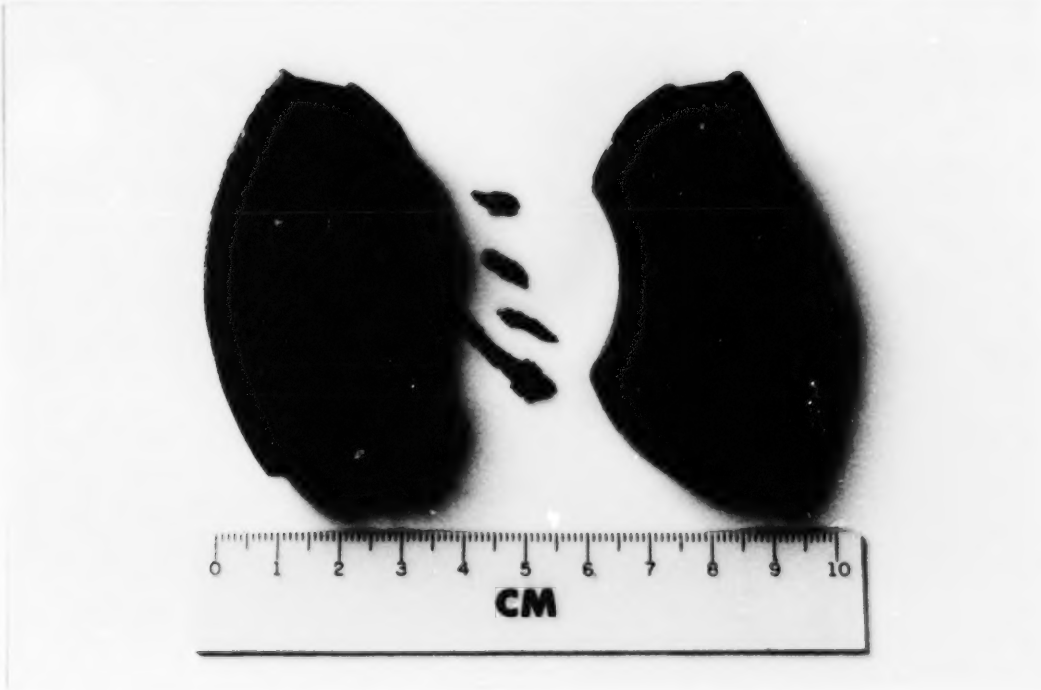


Figure 13. Extent of Wear in Babbitted Thrust Bearings from an Extraction Pump.

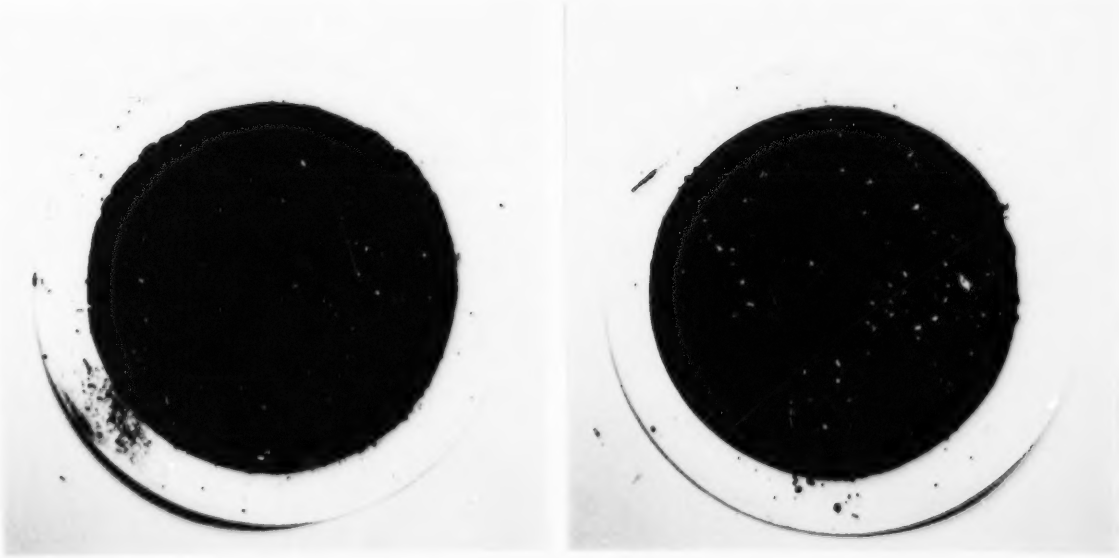


Figure 14. Extent of Ferrous Particles (Light-coloured Areas) in a Helicopter Gearbox Oil Filter. X 1.5

Figure 15. Scanning Electron Microscope Photograph of E52100 Bearing Steel Particle. X 35

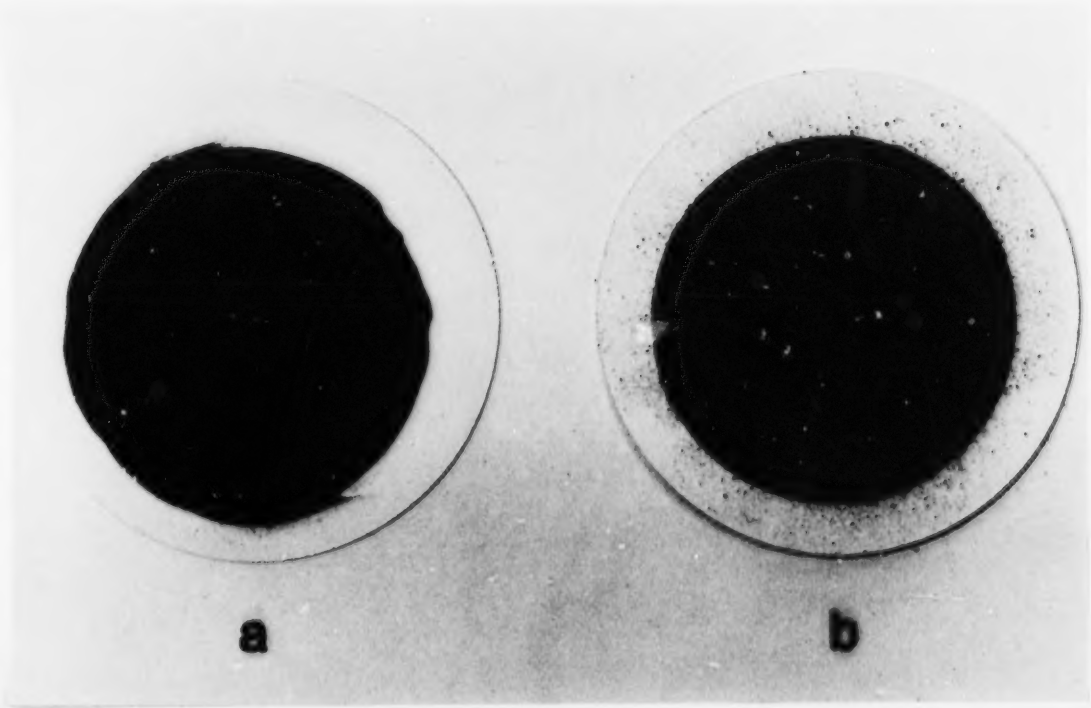


Figure 16. Comparative Amount of Debris in Successive Filters from a Speed Decreaser Gearbox Oil. X 1.5

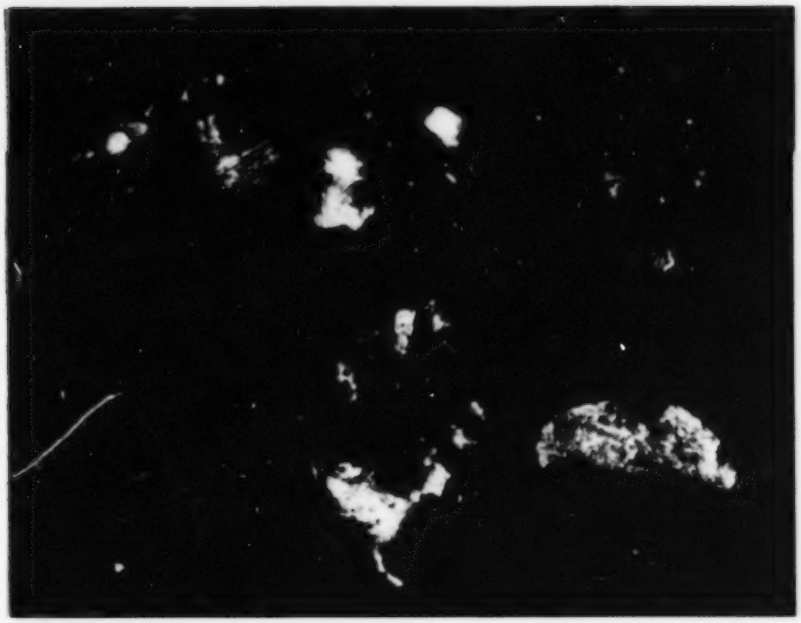


Figure 17. Copper-base Wear Particles Conforming to UNS Specification C87200.
X 40

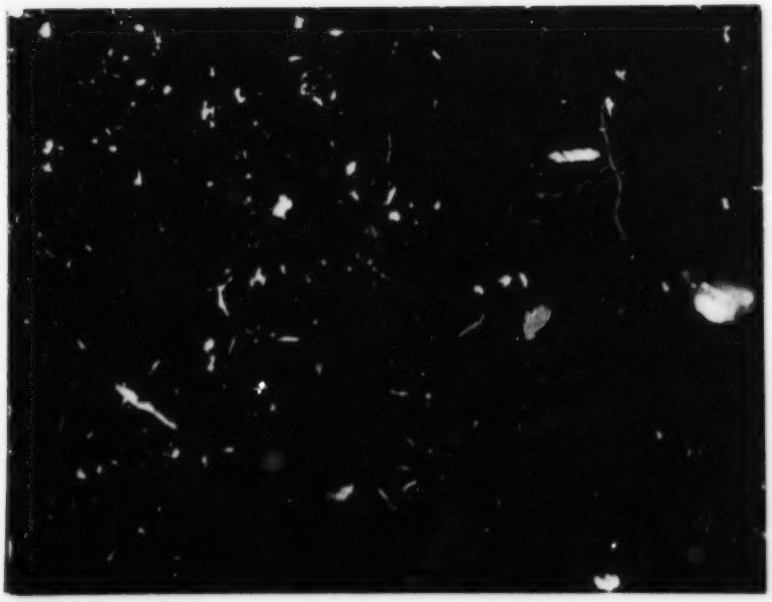


Figure 18. Debris in Gas Turbine Engine Oil Filter at Bearing Failure.
X 25

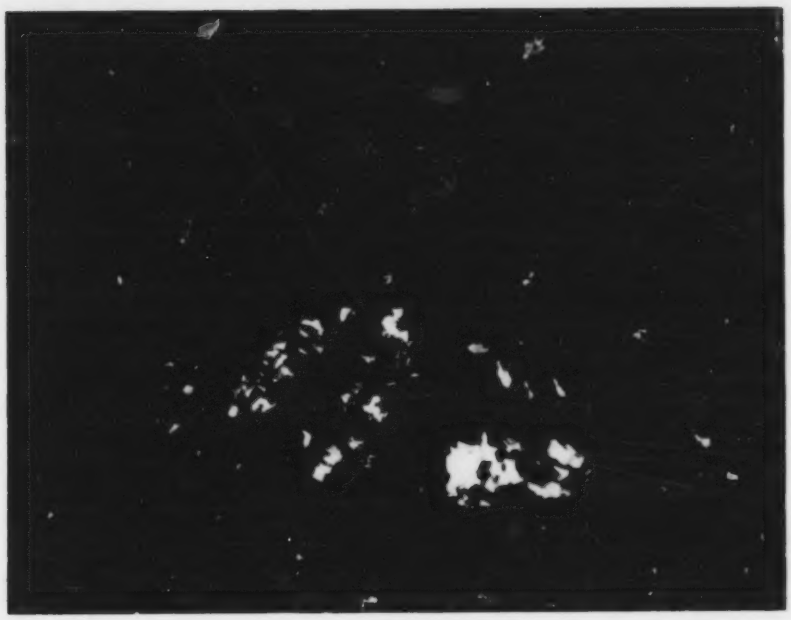


Figure 19. Photograph Showing Copper-base particles (Two Large Particles at Top of picture) and Silver-plated Copper-base Particles (Two Large Particles at Bottom of Picture) in Gas Turbine Engine Oil Filter Debris. X 25

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The diagnostic merits of microscopic inspection and chemical analysis of metallic debris recovered from lubricating oil filters in a variety of oil-vetted machinery are discussed. The filter cleaning method and hov it affects the amount of debris recovered is considered. The significance of representative debris levels and some criteria for establishing these levels are discussed. Abnormal debris accumulations and the corresponding mechanical malfunctions are presented to illustrate hov filter debris analysis can be used to diagnose increased component vear in a variety of machinery. Merits for application of this technique for the diagnosis of machinery condition are considered. The report concludes that this method of assessing vear is particularly suited for equipment fitted with fine lubricating oil filters and is recommended as a complement to other methods currently used for machinery condition monitoring.

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condition monitoring

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